DEFORMATION OF ICE. D. L. Kohlstedt, University of Minnesota (Department of Geology and Geophysics, Pillsbury Hall, Minneapolis, MN 55455; dlkohl@umn.edu)

Introduction: Ice, like other materials, deforms by brittle, ductile, or a combination of brittle and ductile processes. The dominant mechanism of deformation is determined by the conditions to which the mass of ice is subjected. At low temperatures and high differential stresses, deformation occurs predominantly by brittle processes, while at high temperatures and low stresses, ductile process govern flow behavior. As pressure increases with increasing depth, brittle deformation gives way to ductile flow. The transition occurs roughly at a depth at which the lithostatic pressure reaches the level of the differential stress.

In my talk, I will first review aspects of brittle deformation, emphasizing mechanisms of crack nucleation and propagation. I will then focus on ductile deformation or creep of ice, concentrating on recent progress arising from laboratory experiments that provide new insights into mechanisms of plastic flow. Field observations on flow of glaciers and ice sheets provide a direct test of the applicability of laboratory results to large-scale flow of ice. In addition, I will address the role of water on the rheological properties of ice.

Creep of Ice: Creep of most crystalline materials, at least if steady-state flow is attained, is reasonably well described by a flow law of the form:

$$\dot{\varepsilon} = A\frac{\sigma^n}{d^p}\exp\left(-\frac{E+PV}{RT}\right) \qquad (1)$$

where $\dot{\varepsilon}$ is strain rate, A a materials parameter, σ differential stress, d grain size, E activation energy, V activation volume, P pressure, T temperature, and R the gas constant. The values of the stress exponent n and the grain size exponent p are characteristic of the mechanism of deformation.

In the dislocation creep regime, $n = 4.0$ and $p = 0$ for ice; that is, at relatively large grain sizes and/or high differential stresses, deformation is grain-size insensitive [1]. At smaller grain sizes and/or lower stresses, grain-size sensitive flow processes become important. In most materials, diffusion creep dominates at lower stress and finer grain sizes, characterized by $n = 1$ and $p = 2$-3. However, in ice, diffusion creep is not readily accessible. Nonetheless, a significant grain-size sensitive regime exists for ice.

To explore grain-size sensitive creep under laboratory conditions (i.e., strain rates greater than $\sim 10^{-8}\ s^{-1}$) fine-grained samples are essential. Laboratory results obtained on samples with small grain sizes can be extrapolated to larger grain sizes appropriate for flow of glaciers and icy satellites using flow laws such as that in Eq. (1). One grain-size sensitive creep regime has been identified for ice. At constant grain size and temperature, a transition occurs with decreasing stress from dislocation creep to a regime in which grain boundary sliding and basal slip operate in concert to yield $n = 1.8$ and $p = 1.4$ [2].

The constitutive equation describing flow of ice over a wide range of stress, grain size, and temperature conditions can then be expressed as the sum of the contributions from dislocation (dis) creep, with $n = 4.0$ and $p = 0$, and grain-boundary sliding (gbs) accommodated basal slip, with $n = 1.8$ and $p = 1.4$:

$$\dot{\varepsilon}_{tot} \approx \dot{\varepsilon}_{dis} + \dot{\varepsilon}_{gbs} \qquad (2)$$

In Eq. (2), the subscript tot indicates total strain rate, and the approximately equal to symbol suggests that other creep mechanisms (such as diffusion creep) may contribute under yet unexplored deformation conditions. Historically, creep of ice has been described by a single flow law $n = 3$ [3], which is now understood to reflect deformation experiments carried out at the transition between dislocation creep ($n = 4.0$) and grain-boundary sliding accommodated basal slip ($n = 1.8$).

One direct test of laboratory-derived flow laws is comparison with field observations of flow of glaciers and ice sheets. Based on a field experiment on the Barnes Ice Cap, both the microstructure and the stress exponent ($n = 1.7$) observed at low shear stresses of ~0.02 MPa on relatively coarse-grained ice [4] are similar to those obtained in laboratory experiments in the grain-size sensitive creep regime [2]. Likewise, with decreasing stress, a transition from $n = 4.5$ to $n = 1.9$ was reported for flow of ice with a grain size $d > 1$ mm in the Meserve Glacier [5]. More recent field studies also observe grain-size sensitive flow [6]. Hence, the laboratory-derived constitutive equation for ice appears to provide a robust framework for modeling the rheological behavior of Europa.

References:

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